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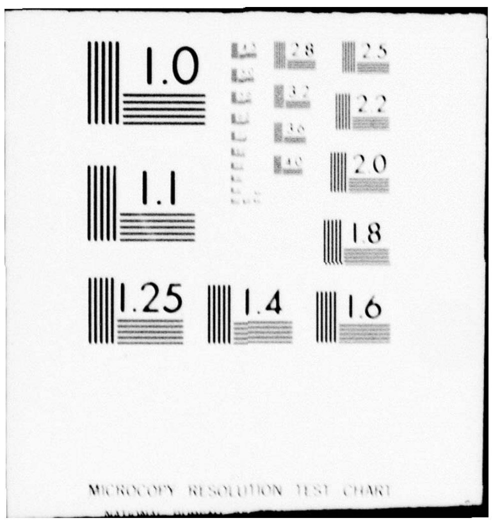
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# OPTICAL–MICROWAVE INTERACTIONS IN SEMICONDUCTOR DEVICES.

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Optical illumination of solid-state microwave devices is a promising method of controlling high-power microwave signals at high speed. Microwave generation, switching, and oscillator injection locking by optical means have been demonstrated.

This program, a study of the physics of semiconductor devices under optical illumination, has the specific goals of achieving optical

injection locking of oscillators, demonstrating millimeter-wave modulation of injection lasers through mode locking, reducing AM and FM noise in solid-state oscillators by optical illumination, and developing new optical and microwave devices with optimal optical-microwave interaction characteristics.

A feasibility study of optically injection locking a millimeter-wave IMPATT oscillator is described. The role of the IMPATT diode's nonlinearity in determining the overall efficiency of the optical injection locking process is discussed. Possible methods of obtaining suitable optical sources for subharmonic optical injection locking of millimeter-wave IMPATT oscillators are suggested. The experimental results of optical injection locking of X-band Si IMPATT oscillators are summarized. A Si IMPATT oscillator of frequency $\sim$8.75 GHz was phase locked to a signal generator tuned to $\sim$2.9 GHz. Substantial frequency noise reduction due to optical illumination and injection locking was also observed. Preliminary results on the study of active mode locking of GaAlAs semiconductor injection lasers is given. The effects of laser medium dispersion, relaxation oscillation, and the spectral broadening mechanism on the success of the mode-locking process are addressed.

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## PREFACE

The following personnel contributed to the research work reported here: H.W. Yen, L. Figueroa, M.K. Barnoski, A. Yariv (consultant), and D.F. Lewis.

## SECTION 1

## INTRODUCTION AND SUMMARY

The use of an optical signal to control solid-state microwave devices has attracted the attention of many researchers. It is a promising method of providing high-speed control (switching, locking, generation, etc.) of microwave signals at high power levels. There are two approaches to accomplishing optical control: illuminate the passive elements in the circuit or illuminate the active elements. An example of the first approach is the optoelectronic switching of microwaves in silicon to generate short bursts of microwave signals with complicated waveforms.[1,2] Examples of the second approach are the reduction of the turn-on phase jitter of TRAPATT oscillators,[3] the optical switching of GaAs IMPATT oscillators,[4] and the optical injection locking of microwave transistor oscillaors.[5]

This program is designed to study the physics of microwave and millimeter-wave semiconductor devices under optical illumination with the specific goals of achieving optical injection locking of oscillators, demonstrating millimeter-wave modulation of injection lasers through mode-locking, optically controlling the AM and FM noise of oscillators, and developing new devices with optimal optical-microwave interaction characteristics.

During the first quarter, we studied the feasibility of optical injection locking of millimeter-wave IMPATT oscillators and began a study of active mode-locking of GaAlAs injection lasers. Experiments on the optical injection locking of X-band Si IMPATT oscillators were carried out also.

Optical injection locking of oscillators in principle is identical to electrical injection locking. The only difference is in the way the locking signal is introduced into the oscillator circuit. In the optical approach, the key is to obtain efficient laser modulation and efficient optical coupling into the active element of the oscillator. To

phase lock a millimeter-wave oscillator requires using subharmonic locking since a millimeter-wave modulated optical source is not available. Therefore, the nonlinearity of IMPATT diodes is an important factor in determining the efficiency of the overall locking process. Optical injection locking of a Si IMPATT oscillator to its third subharmonic signal was achieved. A reduction in oscillator noise through optical illumination and injection locking was observed. We have begun a study of active mode-locking of semiocnductor lasers to determine the effects of laser medium dispersion, laser relaxation oscillation, relative photon and electron lifetimes, and the spectral broadening mechanism on the success of the mode-locking process.

## SECTION 2

## STUDY OF SUBHARMONIC OPTICAL INJECTION LOCKING OF OSCILLATORS

Optical injection locking of transistor oscillators has been demonstrated at low microwave frequencies with both fundamental and subharmonic locking. To extend this technique to the millimeter-wave frequency region, subharmonic locking will have to be used since no millimeter-wave modulated optical source exists.

The phenomenon of injection locking of oscillators has been under study for several decades. In principle, optical injection locking is exactly the same as electrical injection locking except for the way the locking signal is introduced into the oscillator circuit. The basic equation describing the injection-locking process is[6]

$$\frac{d\alpha}{dt} = -\Delta\omega_L - \frac{\omega_o}{2Q} \tan\theta, \qquad (1)$$

where $\alpha$ is the relative phase angle between the injected signal and the oscillator output signal; $\theta$ is the phase angle of the response function of the active nonlinear element in the oscillator; Q is the external quality factor of the resonant circuit; $\omega_o$ is the oscillator output frequency; and $\Delta\omega_L = \omega_L/n - \omega_o$, where n is the order of harmonics, and $\omega_L$ is the frequency of the injected signal. In general, $\tan\theta$ is a function of $\alpha$.

Important information about the injection-locking process can be derived directly from Eq. 1. For instance, under stable injection locking,

$$\frac{d\alpha}{dt} = 0 ,$$

which leads to

$$\Delta\omega_L = - \frac{\omega_o}{2Q} \tan\theta. \qquad (2)$$

Therefore, the locking range is given by

$$(\Delta\omega_L)_{max} = -\frac{\omega_o}{2Q}\,[\tan\theta(\alpha)]_{max} \quad , \tag{3}$$

and, within the locking band, Eq. 2 gives, for a given frequency deviation betwen $\omega_o$ and $\omega_L/n$, the phase angle after locking.

So the problem of analyzing injection-locked oscillators becomes that of finding tan $\theta$ for the given nonlinear active element in the oscillator circuit. The nonlinearity of the active element can be approximated by a polynomial of the following form:

$$i = f(v) = a_o + a_1 v + a_2 v^2 + a_3 v^3 + \ldots + a_m v^m \quad , \tag{4}$$

where m should be at least equal to the order of the required locking. The total input to the nonlinear element is the sum of the oscillator output feedback and the injected locking signal. If $\omega_o$ and $\omega_L$ are assumed to be harmonically related, then

$$v_{in} = v_o \cos\omega t + v_L \cos n(\omega t + \alpha) \quad . \tag{5}$$

By substituting Eq. 5 into Eq. 4, the phase angle $\theta$ of $i/v_{in}$ at frequency $\omega$ can be calculated.

For fundamental locking, set n equal to 1:

$$(\tan\theta)_1 = x\,\frac{\sin\alpha}{1 + A_1\cos\alpha} \quad , \tag{6}$$

where

$$x = \frac{v_L}{v_o}$$

$$A_1 = \frac{k_1 + 3k_3\,(3 + x^2)/4}{k_1 + 3k_3\,(1 + x^2)/4}\; x$$

$$k_i = a_i v_o^i \; .$$

We have also assumed that $k_1 >> k_2$, $k_3$ and that $k_i = 0$ for $i > 3$.

For subharmonic locking, n is a fraction, and $(\tan\theta)_n$ can be calculated to be

$$(\tan\theta)_n = A_n \frac{\sin\alpha}{1 + A_n \cos\alpha} , \tag{7}$$

where

$$A_{1/2} = \frac{\frac{1}{2} k_2 x^2}{k_1 + \frac{3}{4} k_3 (1 + 2x^2)} \quad \text{(for } n = 1/2\text{)} \tag{8}$$

$$A_{1/3} = \frac{\frac{1}{4} k_3 x^3}{k_1 + \frac{3}{4} k_3 (1 + 2x^2)} \quad \text{(for } n = 1/3\text{)} . \tag{9}$$

To calculate the locking range, we need $(\tan\theta)_{max}$. Differentiating Eqs. 6 and 7 yields

$$(\tan\theta)_{max} = \pm \frac{x}{\sqrt{1 - A_1^2}} \quad \text{(for fundamental locking)}$$

and

$$(\tan\theta)_{max} = \pm \frac{A_n}{\sqrt{1 - A_n^2}} \quad \text{(for subharmonic locking)} .$$

For a small injecting signal ($x << 1$), we have

$$(\tan\theta)_{1,max} \approx \pm x \quad \text{(for } n = 1\text{)}$$

and

$$(\tan\theta)_{n,max} \approx \pm A_n \quad \text{(for } n = 1/2, 1/3\text{)}$$

at $\alpha = \pm \pi/2$. Thus, the relation between the locking range and locking gain of oscillators is quite complicated. For quantitative evaluation, numerical coefficients $a_1$, $a_2$, and $a_3$ need to be determined. These can be obtained from a large-signal analysis of the IMPATT diode, or they can be measured experimentally.

One problem encountered with optical injection locking is that the efficiency of optical absorption of the IMPATT diode is poor. Conventional diode packaging is not suitable for this purpose because it is difficult to obtain uniform illumination over the entire area of the diode. Typically, the diode would have a diameter of 50 μm, and optical radiation from a cw GaAlAs laser (0.82 μm in wavelength) would have an absorption coefficient of 1000 $cm^{-1}$ in silicon. Therefore, for 10 μm of traveling distance, the optical intensity will drop to $e^{-1}$ (or 37%) of its initial value. Thus, although the utilization of optical power is more efficient with edge illumination, the illumination is nonuniform. Stronger absorption near the device edge might generate microplasma in these regions, trigger localized avalanche breakdown, and cause the device to operate noisily. Millimter-wave IMPATT diodes are normally mounted with the active side down for better heat-sinking. The substrate can be thinned to less than 10 μm. If a ring contact is used on the substrate side of the diode, we will have a large window for illumination. Although 60% of the light will be absorbed by the substrate, the overall illumination of the active region will be much more uniform. This means that the oscillator will operate more quietly and will therefore be more attractive for our purpose. Also, the light absorbed by the substrate is not completely wasted since optical illumination can reduce the resistivity of the substrate and help improve the overall efficiency of the diode.

For subharmonic locking to work, the nonlinearity of the active device should be reasonably large, as evident from Eqs. 8 and 9. The nonlinearity of the IMPATT diode depends on its biasing and the frequency of oscillation. By adjusting these two parameters, it might be possible to optimize the nonlinear effect. But, because of the saturation effect, IMPATT diodes operating in the large signal mode (such as in an oscillator) will always have some nonlinearity.

To achieve optical injection locking, there are two basic approaches. Figure 1(a) illustrates one of these, in which the optical signal modulated at some suitable millimeter-wave frequency is guided directly into the active region of the IMPATT oscillator. The IMPATT diode acts as the optical detector, the harmonic converter, and the millimeter-wave oscillator. The merit of this approach is its simplicity; its disadvantage is that poor optical coupling and nonlinear upconversion can be expected to cause efficiency to be low. Figure 1(b) illustrates the second approach, in which, to improve the coupling and converion efficiencies, the optical signal is not used to illuminate the IMPATT diode directly. A separate optical detector and a harmonic converter are used in front of the IMPATT diode to detect the optical signal and upconvert it to the IMPATT's fundamental frequency. Then fundamental electrical injection locking is used to achieve the locking. The merit of this approach is that each single step can be optimized for its specific function, with the tradeoff being the complexity. However, the second approach can eventually evolve into a new type of millimeter-wave source in which all the components are integrated into a single chip package with compactness and minimal coupling loss between stages.

The efficiency of injection locking of oscillators decreases as the order of the subharmonic increases. Thus, it is important to have millimeter-wave modulated optical sources and keep the subharmonic order low. It has been shown both thoeretically and experimentally that direct modulation of injection lasers has a practical limit of less than 10 GHz. Therefore, a different approach is needed to modulate the injection laser output at low millimeter-wave frequencies. One promising method is through mode locking. It might be possible to obtain 20-psec pulses at a 10-GHz repetition rate by modulating a GaAlAs laser in an external cavity configuration.

Once a 10-GHz repetition rate of 20-psec pulses is achieved, wave splitting and recombining techniques can be used to obtain optical pulse trains with repetition rates equal to multiples of 10 GHz (as shown in Figure 2). For an optical pulse train with a repetition rate

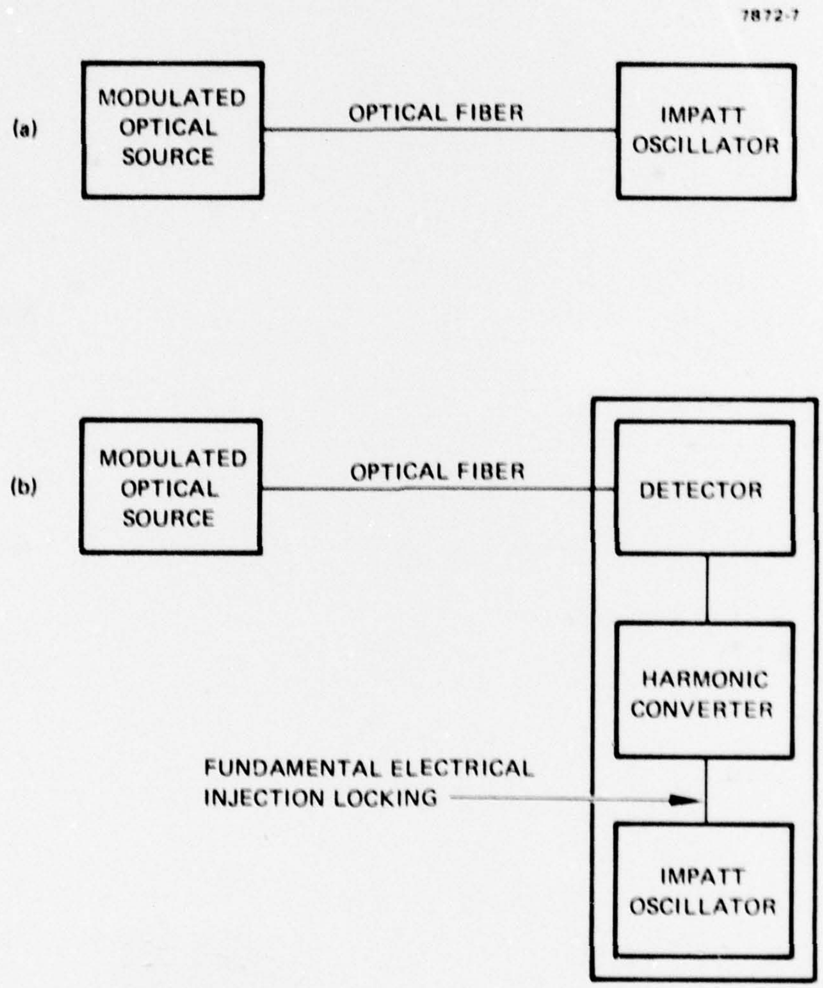


Figure 1. Two approaches to optical injection locking of millimeter-wave IMPATT oscillators.

F, the time lapse between two consecutive pulses is 1/F. To increase the pulse rate by a factor of m would require m pairs of beam splitters separated by a distance d given by

$$d = c \times \frac{1}{F} \times \frac{1}{m} \times \frac{1}{2} = \frac{c}{2mF} .$$

For F = 10 GHz and m = 2, d = 0.75 cm. Of course, the optical pulse width should be narrow compared to the new period 1/mF.

There are a few variations of the basic scheme shown in Figure 2 that can be used to increase the pulse rate, such as optical fiber delay lines and integrated optical circuits using channel waveguide directional couplers. These approaches are especially useful if the original optical pulse repetition rate is high enough or if the delay times involved are small. In the integrated optical circuit approach, the approximate circuit can be fabricated on an $LiNbO_3$ substrate by photolithography while the fine tuning is done using the electrooptic effect.

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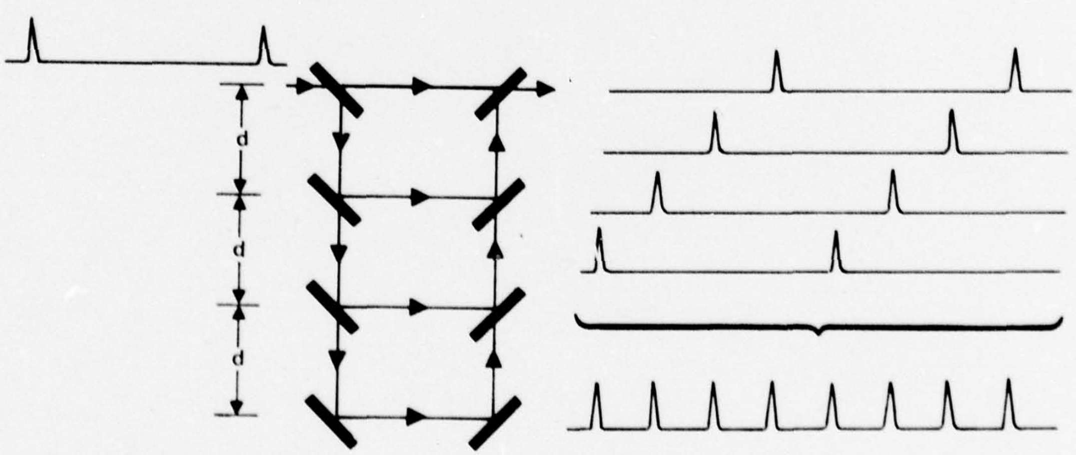


Figure 2. Wave splitting and recombining techniques for multiplying the optical pulse repetition rate.

## SECTION 3

## OPTICAL INJECTION LOCKING OF Si IMPATT OSCILLATORS

Optical injection locking of Si transistor oscillators and GaAs FET oscillators has been demonstrated with both fundamental and subharmonic injecting signals; switching of GaAs IMPATT oscillators with optical pulses has also been achieved.[4,5] However, optical injection locking of IMPATT oscillators had not previously been attempted. This section reports the successful locking of X-band Si IMPATT oscillators by optical injection.

The IMPATT diodes used in this experiment were packaged commercial devices from Hewlett-Packard (HP 5082-0435). The frequency of operation was 8 to 12 GHz with an operating voltage of ∿90 V and operating current of ∿30 mA. The diodes were mounted in a microwave package, as shown in Figure 3. The devices were hermetically sealed in a ceramic sleeve with metallic contact on each end. To expose the diode chip for illumination, we cut a small groove in the ceramic sleeve using a wire saw. The diode package was then mounted in an X-band microwave cavity with a waveguide tuning short on one side and an output coupling probe on the other side. A small hole was drilled in the side of the cavity such that an optical fiber could be fed through the cavity wall to allow the output of a modulated injection laser to be coupled to the IMPATT chip. The experimental setup is sketched in Figure 3. The optical coupling efficiency to the IMPATT diode was poor due to a protective coating that surrounds the chip to prevent edge leakage and breakdown. Nevertheless, third subharmonic injection locking was observed with this arrangement.

Figure 4(a) shows the source signal at 2.918 GHz and -2 dBm; this signal is used to modulate a GaAlAs laser. Figure 4(b) is the spectrum analyzer display of the IMPATT oscillator output at 8.754 GHz and 15 dBm. In our experiment, the IMPATT output spectrum was monitored with the spectrum analyzer while the laser modulation frequency was tuned manually around 2.918 GHz. Figure 5(b) shows the IMPATT oscillator

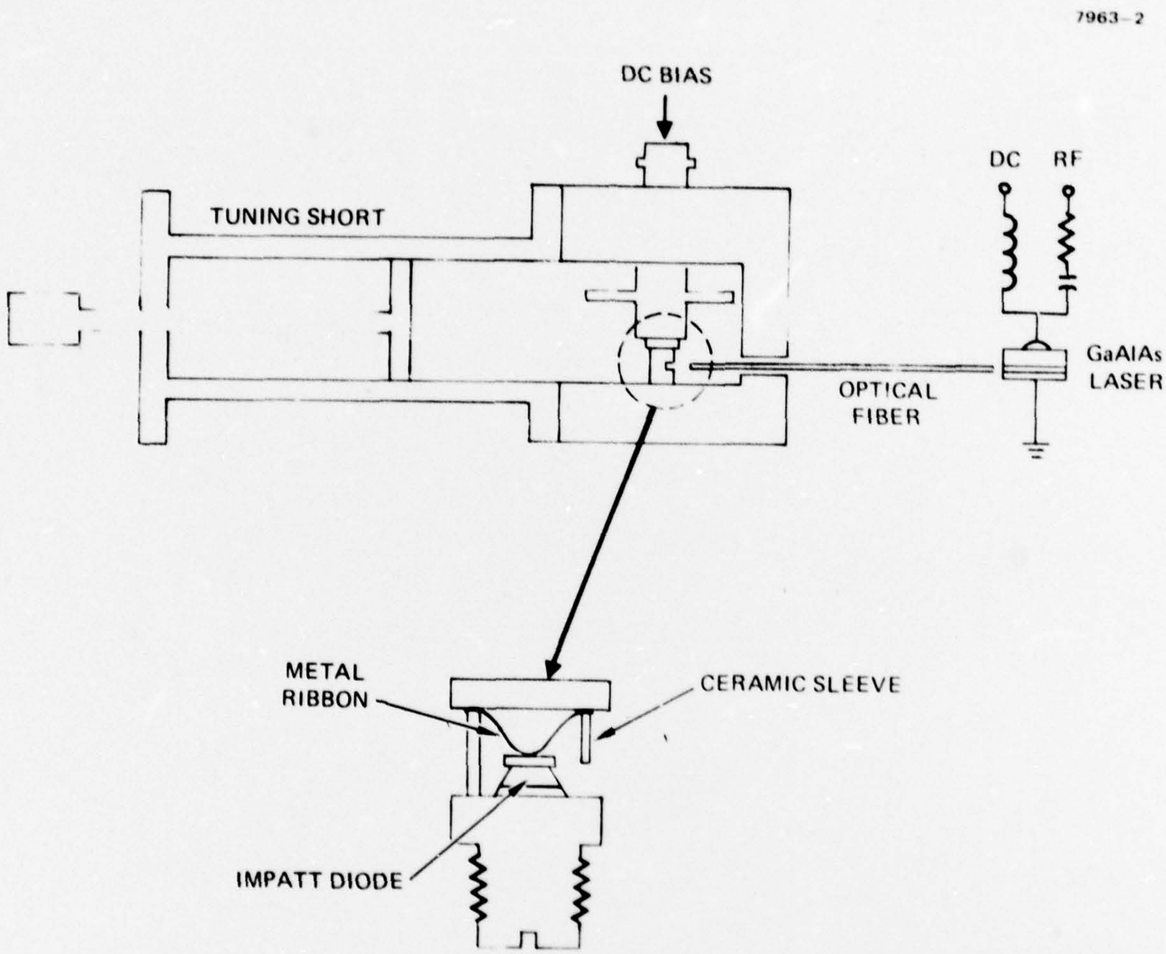


Figure 3. Experimental setup of the optical injection locking of Si IMPATT oscillators.

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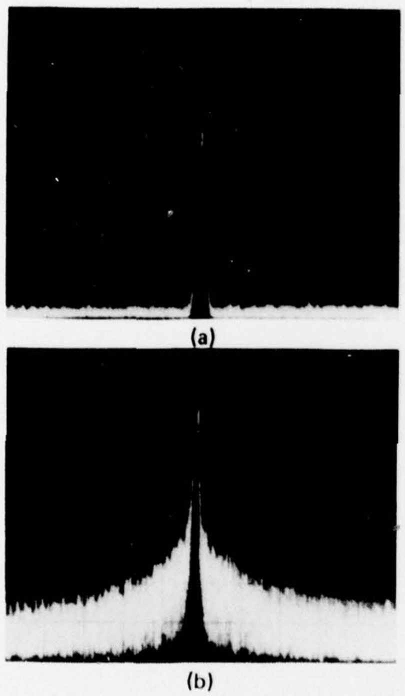

(a) Injection signal

(b) Free running IMPATT oscillator output

Figure 4. Oscillator spectra.

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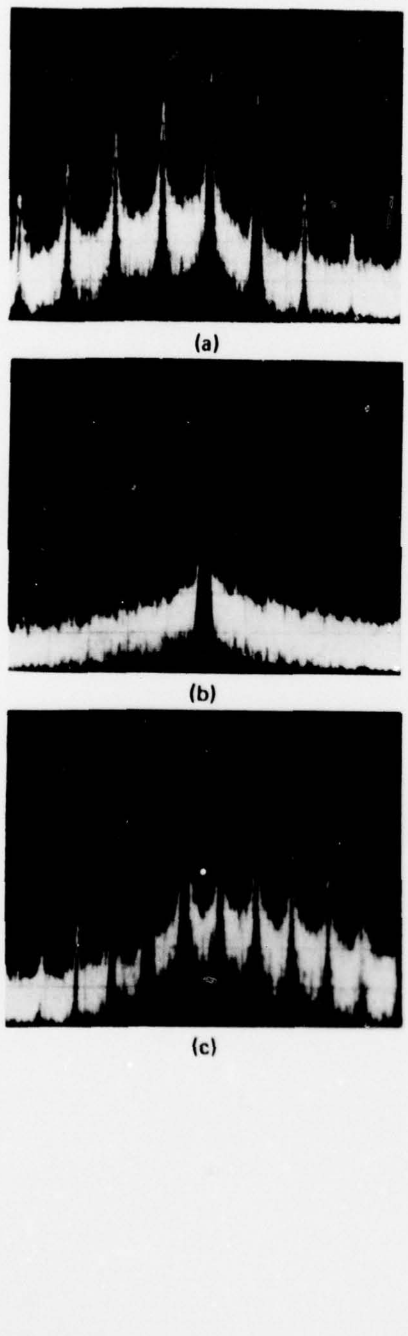

Figure 5.
Si IMPATT oscillator output spectra under injection locking.

output spectrum just inside the locking band; Figures 5(a) and 5(c) show it just outside the locking band. The total locking band in this case was only about 200 kHz. A comparison of Figure 4(b) with Figure 5(b) shows that the spectrum of the locked oscillator output was cleaner than that of the free running output. Figure 6 shows the sequence of injection locking of a different IMPATT oscillator. The bias current in this case was smaller (∿18 mA), and the cavity was tuned to the lower frequency end (7.628 GHz). The IMPATT was not oscillating with a pure single frequency, as evident from the spectrum display. However, in this case the locking process was rather efficient; a total locking band of 3 MHz was achieved. There was evidence that the nonlinearity of the IMPATT diode depends strongly on its bias condition; the nonlinear effect seems to be larger at lower bias current.

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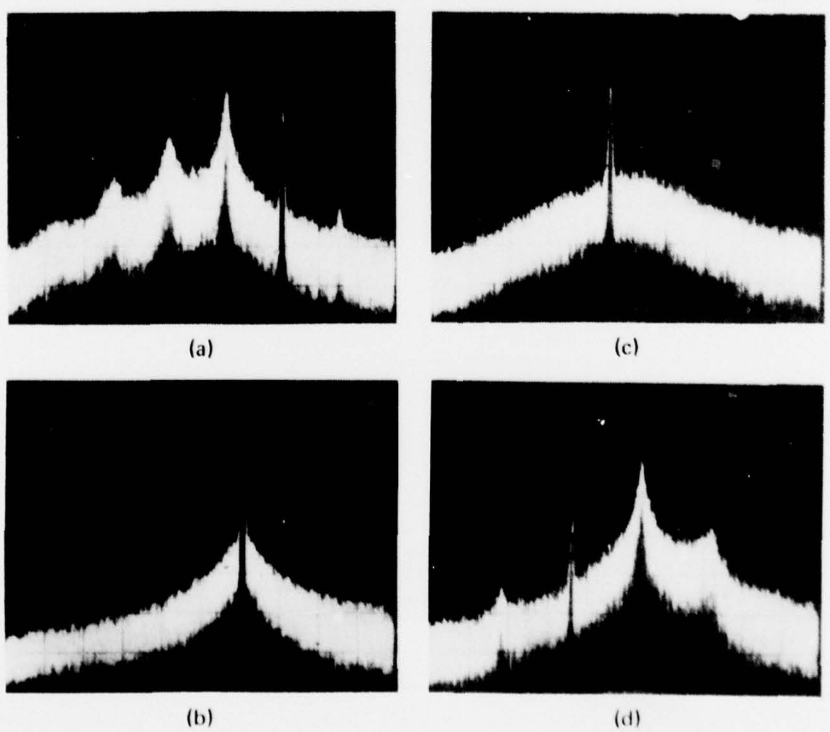
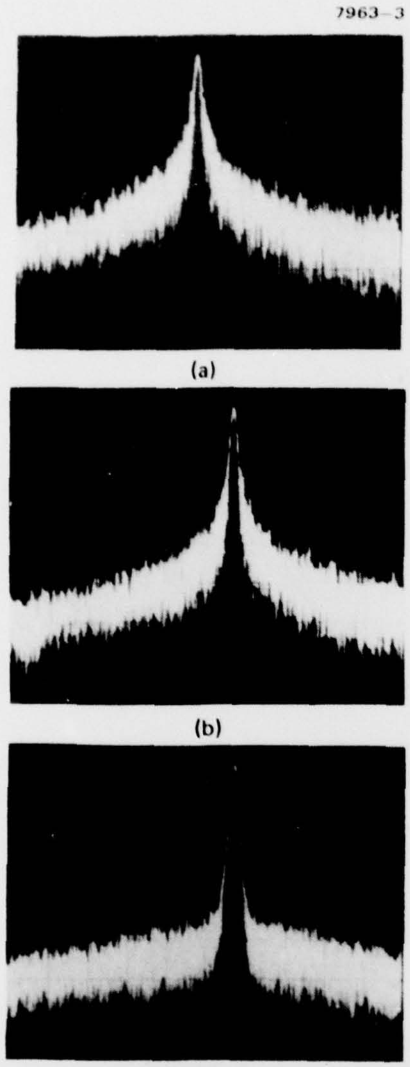



Figure 6. Sequence of Si IMPATT oscillator spectrum under injection locking.

Figure 7 shows three output spectra from the same IMPATT oscillator. Figure 7(a) is the free-running oscillator output at 8.113 GHz and 14 dBm. Figure 7(b) is the spectrum of the same oscillator under optical illumination with constant intensity. There is an upward frequency shift of 80 kHz and a substantial frequency noise reduction ($\sim$8 dB) around the oscillation frequency. Figure 7(c) is the output spectrum of the oscillator phase locked to a signal source at 2.704 GHz. There is a further reduction of FM noise by about 5 dB. Thus, an overall frequency noise improvement of 13 dB is accomplished by the optical injection locking process in the IMPATT oscillator output.

As a comparison, we also examined the behavior of a Si transistor oscillator under similar conditions. Figure 8(a) shows the free running oscillator output, which has a frequency chirping of about 60 kHz at about 2.6 GHz. Figure 8(b) shows the spectrum of the same oscillator when illuminated by a few milliwatts of optical power. The oscillation frequency shifted downward by about 15 MHz, and the frequency chirping was enhanced to about 190 kHz. The frequency noise increased by roughly 10 dB. Figure 8(c) shows the spectrum of the locked oscillator (fundamental locking). The frequency chirping was quenched since the locking band in this case was about 2 MHz. The frequency purity of the oscillator was substantially improved over the free running case, especially within $\pm$100 kHz of the oscillation frequency.

The different behavior between the IMPATT oscillator and the Si transistor oscillator under optical illumination is not yet completely understood. However, it is believed that the role the photo current plays is different in these two devices. This study will continue during the next quarter.




(a) Free running

(b) Illuminated

(c) Optically injection locked

Figure 7. IMPATT oscillator output spectrum.

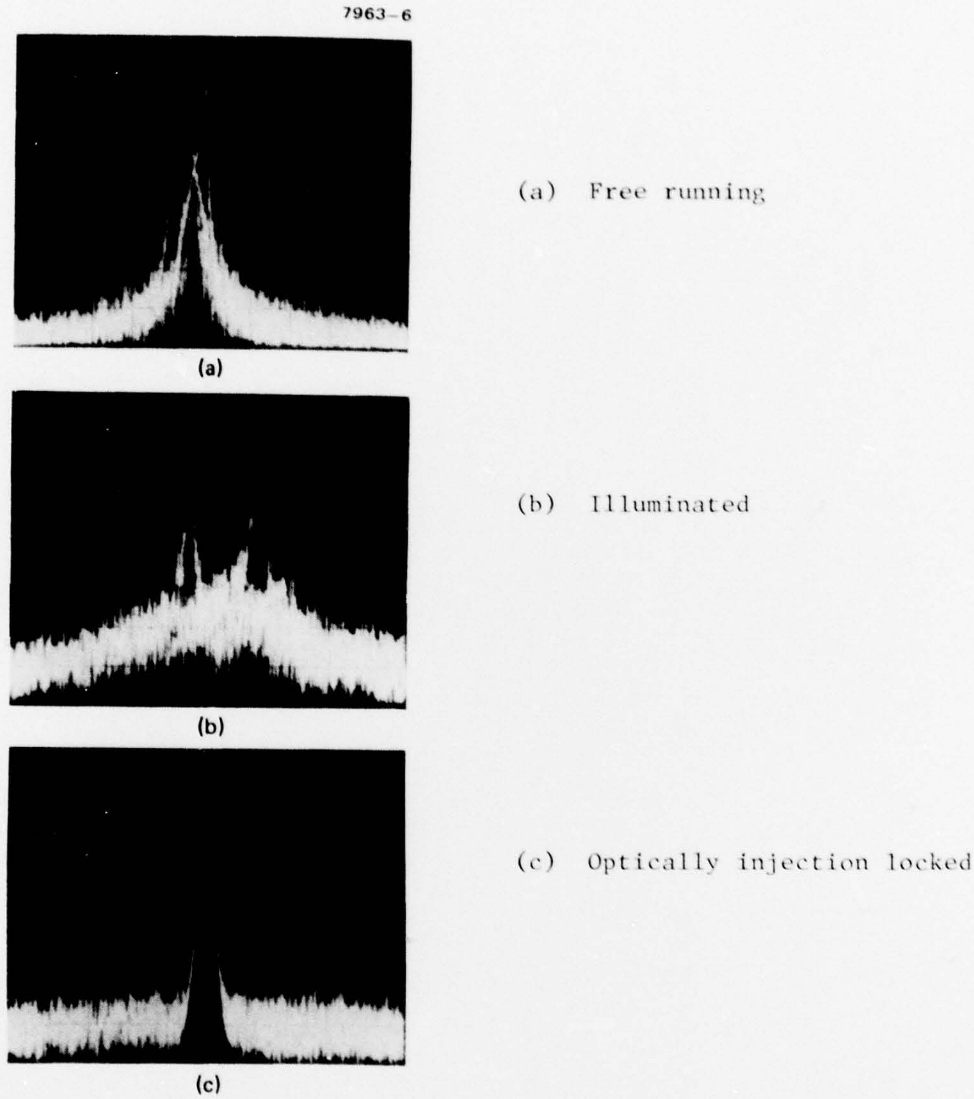



Figure 8. Spectrum of transistor oscillator output.

## SECTION 4

## STUDY OF MODE LOCKING OF INJECTION LASERS

The goal of this study is to achieve mode locking of GaAlAs double-heterostructure (DH) injection lasers to obtain a train of ultra-short optical pulses. Our approach consists of (1) a theoretical study on the ultimate limit of pulse width and pulse repetition rate and (2) an experimental attempt to mode lock a GaAlAs laser in the external cavity configuration.

The following problems are being considered in our theoretical study:

- Effect of laser medium dispersion
- Effect of laser relaxation oscillation
- Effect of the ratio of photon lifetime to carrier lifetime
- The nature of the line broadening mechanism and its relation to mode locking.

Previous investigators have felt that semiconductor lasers cannot be easily mode locked due to the material dispersion near the wavelength of laser emission.[7,8] This was based on results using homojunction lasers at 77°K. The dispersion effect is greater at 77°C than at 300°K, where most current devices operate. The dispersion reduces the coupling between longtiduinal modes and leads to the locking of only a few modes. This in turn broadens the pulse width of the mode-locked laser. However, in a recent experiment,[9] the effect of dispersion does not appear to be significant (at least in the external cavity situation) and probably is no worse than the effect of the prism in mode-locked dye lasers. The effect of dispersion can be reduced further by using a large optical cavity (LOC) structure.[10,11] In an LOC laser, the transverse confinement factor is lower. This leads to an optical mode that propagates primarily in a layer having little material dispersion at the lasing wavelength.

The problem of relaxation oscillations in reference to mode-locking has been treated by Mohn[12,13] and Haus.[14] Haus suggested that the existence of relaxation oscillation can suppress mode locking if the period of the oscillation is too short to allow for the build-up of the mode-locked pulses within one cycle of the oscillation. There are several possible ways to circumvent this problem. For example, a laser with reduced relaxation oscillations could be used. Such lasers include the channeled substrate planar structure laser (CSP),[15] the buried heterostructure laser (BH),[16] and the transverse junction stripe laser (TJS).[17] Another approach would be to use an external cavity to lower the relaxation oscillation frequency. The frequency of relaxation oscillation is given by

$$\omega_o = \left(\frac{1}{\tau_p \tau_s}\right)^{1/2} \left(\frac{I}{I_{th}} - 1\right)^{1/2} ,$$

where $\tau_p$ is the cavity lifetime (photon lifetime), $\tau_s$ is the spontaneous recombination time, $I_{th}$ is the laser threshold current, and I is the laser driving current. $\tau_s$ is typically 1 to 3 nsec, and the cavity lifetime $\tau_p$ is given by

$$\tau_p = \frac{\ell n}{\varepsilon C_o} ,$$

where $C_o$ is the speed of light in vacuum, n is the index of refraction of the active region, $\ell$ is the length of the laser, and $\varepsilon$ is the fractional optical intensity loss per pass. Therefore, to reduce $\omega_o$, we can use an external cavity such that the total cavity length is L and the cavity lifetime becomes

$$\tau_p' = \frac{L + \ell(n - 1)}{\varepsilon\ C_o} .$$

For $\ell$ = 350 $\mu$m, n = 3.5, $\varepsilon$ = 0.7, and L = 15 cm, we have $\tau_p$ = 5.8 psec and $\tau_p'$ = 0.72 nsec. Thus, in this example, the relaxation oscillation frequency is improved by a factor of 11 by using 15 cm of external cavity.

To mode lock a laser, the applied frequency of modulation must satisfy the condition

$$f = \frac{mC_o}{2nL} ,$$

where m is an integer greater than or equal to one. For a laser without an external cavity and with L = 1 mm, f is about 43 GHz; for a laser with an external cavity and with L = 15 cm, f is only about 1 GHz. One obvious requirement is that the pulse width of the mode-locked pulse be less than the period of oscillation 1/f. In the case of no external mirror and L = 1 mm, $\tau_{pulse}$ < 24 psec is required. The external cavity case requires $\tau_{pulse}$ < 1 nsec.

Theoretically, for an inhomogeneously broadened system, the minimum pulse width $\tau_{min}$ is determined by the spectral width $\Delta\nu$ of the oscillating modes. For many injection lasers, the spectral width is about 20 Å, which corresponds to a $\tau_{min}$ of 1.4 psec. Earlier workers,[18] however, obtained much wider pulses, probably because of incomplete mode locking.

In the previous calculation of the pulsewidth during mode locking, we assumed that the semiconductor laser was inhomogeneously broadened. But some investigators have felt that the semiconductor laser is homogeneously broadened when the material is uniform. Several groups[15-17] have recently obtained single longitudinal mode operation over a wide range of current when using structures with well stabilized lateral modes. It is known that one property of a homogeneously broadened laser system is single-longitudinal mode operation under steady-state excitation. With these thoughts in mind, it is worthwhile to examine mode locking based on the assumption of a homogeneously broadened system. This problem is not as intuitive as the previous case since mode locking would not be expected to be present. Experiments reveal that mode locking can be obtained much as in the inhomogeneously broadened

system. According to Yariv,[19] the presence of internal modulation leads to a continuous transferring of power from the high-gain mode to lower-gain modes (i.e., modes that would not normally oscillate). This power can be viewed as that of the sidebands at $(\omega_o \pm n\omega_m)$ of the mode at $\omega_o$ created by modulation at $\omega_m$. Thus, the physical phenomenon is not mode locking but rather is mode generation. The net result is the existence of a large number of oscillating modes with equal frequency spacing and fixed phases, as in the inhomogeneous case.

The pulse width in this case is given by

$$\tau_{pulse} = \frac{(2 \ln 2)^{1/2}}{\pi} \left(\frac{2g_o}{\delta_e^2}\right)\left(\frac{1}{\Delta\nu_{axial}\Delta\nu}\right)^{1/2} ,$$

where

$g_o = \gamma_{max}\ell$ ($\gamma_{max}$ is the peak gain, $\ell$ is the length of the laser medium)

$\delta_e^2$ = amplitude of loss modulation

$\Delta\nu_{axial}$ = mode spacing in Hz

$\Delta\nu$ = gain linewidth in Hz.

For typical parameters, $\tau_{pulse}$ is found to be

$$\tau_{pulse} = 0.268 \times 10^{-12} \text{ sec} \quad \text{for } \delta_e = 1$$

$$\tau_{pulse} = 1.44 \times 10^{-12} \text{ sec} \quad \text{for } \delta_e = 0.1$$

$$\tau_{pulse} = 4.55 \times 10^{-12} \text{ sec} \quad \text{for } \delta_e = 0.01 .$$

From the discussion above, it appears that mode locking of injection lasers is possible using an external cavity. In this situation, the effect of relaxation oscillation and dispersion are reduced. If a homogeneously broadened laser system is used (such as CSP, BH, or TJS lasers), ultrashort pulses with variable pulsewidth can be obtained.

In our experimental study, a setup similar to that shown in Figure 9 will be used. The total cavity length L is about 5 cm, which corresponds to a required modulation frequency of $\sim$3 GHz.

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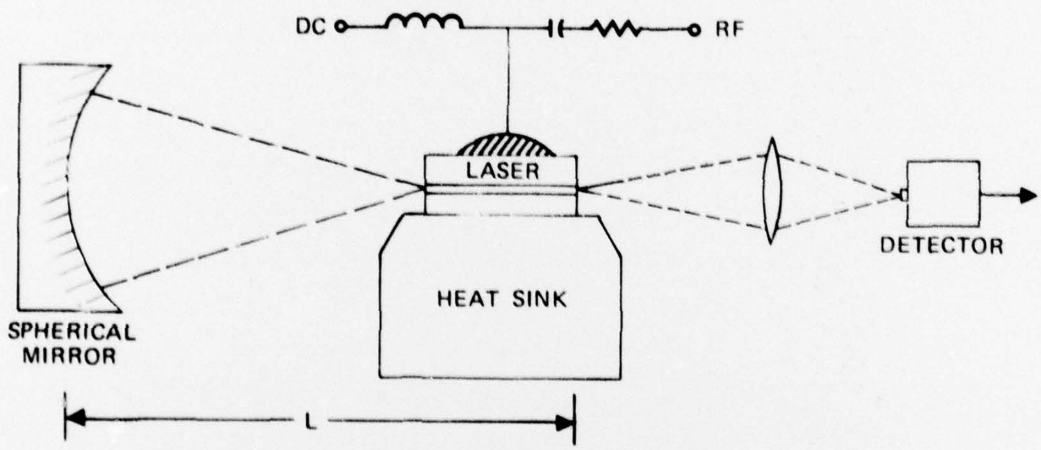


Figure 9. Schematic of injection laser mode-locking experimental setup.

## SECTION 5

## PLANS FOR THE NEXT QUARTER

During the next quarter, we will continue the optical injection locking experiment with Si IMPATT oscillators. Emphasis will be on increasing the efficiency of light coupling to the diodes and on extending to higher frequency bands. The feasibility study of injection locking a millimeter-wave IMPATT oscillator optically will be completed, and a conclusion will be made as to whether this is a viable approach. Work on oscillator noise reduction, phase jitter reduction, and frequency stabilization by optical illumination will begin with X-band IMPATT oscillators. Active mode locking of GaAslAs injection lasers is under investigation. In the next quarter, we will attempt to find the ultimate limit of mode-locked pulse width and of pulse repetition rate. Experimental work with the external cavity configuration will continue; the pulse repetition rate will be about 3 GHz. We will also analyze in detail the structure of a modified GaAs FET to finalize the design. In this new structure, we propose to introduce a GaAlAs layer between the GaAs channel layer and the semi-insulating GaAs substrate so that the GaAs channel layer will serve as an optical waveguide. This should help guide the incident optical signal for more efficient interaction. Our analysis will focus on the effect of this additional layer on GaAs FET performance.

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